Power Control Method for Reducing Circulating Current in Parallel Operation of DC Distribution System

Soo-Cheol Shin*, Hee-Jun Lee*, Jung-Hyo Lee*, Young-Ho Kim*, Taeck Kie Lee** and Chung-Yuen Won†

Abstract – In general, for a large power system like DC distribution system for buildings, several power converters are modularized for parallel operation. However, in parallel operation, inconsistency of parameters in each module causes circulating current in the whole system. Circulating current is directly related to loss, and, therefore, it is most important for the safety of the power system to supply the suitable current to each module. This paper proposes a control method to reduce circulating current caused during parallel operation. Accordingly, the validity of parallel operation system including response characteristics and normal state was verified by simulation and experiment result.

Keywords: DC distribution, Circulating current, Parallel system, AC/DC converter, Dc/Dc converter, Power control

1. Introduction

Recently limited fossil fuels have led to increase interest in renewable energy with a DC output and efficient energy management in the power industry. Also, the loads that require DC power in modern industries have increased constantly along with the electronic systems. In case of DC power, power-factor is always kept at 1, and the absence of frequency and rotational directional allow easy circuit interpretation. By using a DC power system, it can be formed simply by using a one-stage power conversion system for DC to DC conversion when supplying power to DC loads. [1-2] Therefore, there is a growing interest in DC power system.

In general, for a large power system like DC distribution system for buildings, several power converters are modularized for parallel operation. This method can use an element with low current rated, and can achieve standardization of all power modules in designing the system. Also, each module is designed as the optimum capacity when designing hardware, which allows cost-effective design. When controlling DC voltage of two or more power converters, there can be a difference in voltage caused by error in sensor measurement, gain error in controller, line impedance constituent, and difference in characteristics of power semiconductor devices. Therefore, circulating current is necessarily caused to the system. Circulating current can cause over-current and conduction loss in each element, reducing the efficiency of the whole system. Also, it can reduce the response characteristics of output voltage with variable load. For those reasons, it can have various negative effects on the connected devices and deteriorate power quality. [3-4] Fig. 1 shows the path of circulating current in DC distribution system.

Recently, several control methods have been proposed to reduce circulating current. Widely known methods include adding 3-phase coupled inductor to AC source,[5] speed droop between active power(P)-frequency(f) and voltage droop between reactive power(Q)-voltage(V). [6-9] However, these solutions increase the volume, weight, cost, etc., of the entire system because of the need to set up additional hardware. Furthermore, in the proposed topology, AC/DC converter is connected to DC/DC converter with no frequency in series, droop control cannot be applied.

In this paper, control method to reduce circulating current is proposed. Therefore, validity of parallel operation system including response characteristics and
normal state are verified by simulation and experiment result.

2. Parallel System in DC Distribution

The three-phase AC/DC converter for building DC distribution system must be converted AC voltage to DC voltage to supply DC power. Also, operating a building elevator by using a DC power may produce regenerated energy, thereby requiring bi-directional power conversion system of the power with the AC grid. Bidirectional power control system can help efficient energy use in a building, when connected with a new renewable energy generation system like Building Integrated Photovoltaic System (BIPV) or Energy Storage System (ESS). The three-phase AC/DC converter was controlled at 700[Vdc], and the distribution voltage was controlled at 380[Vdc] by additionally connecting a DC/DC converter capable of bi-directional buck/boost power control. Fig. 2 shows DC distribution system for building applications. [11]

Fig. 2 shows proposed DC distribution system for building applications. The three-phase AC/DC converter has an initial charging circuit so that it can operate with the capacitor of DC-link completely discharged. The initial charging circuit, when supplying power to a completely discharged capacitor, prevents inrush current and, therefore, damage of anti-parallel diode combined in IGBT in three-phase AC/DC converter. In grid connection, a three-phase AC/DC generally uses switching frequency range of a few kHz. This switching frequency range increases harmonic of the input current, and LCL filter was used to prevent it. [12-13] The three-phase AC/DC converter is a device that conversion AC power into DC power, capable of acquiring stepped-up DC voltage using AC power. It can also control power factor, active and reactive power. [14] In general, to control 3-phase power, the reference frame transformation theory is applied to convert the AC voltage and current to two-phase d-q axis voltage and current. Bi-directional DC/DC converter is composed in three parallel systems to distribute the current imposed on the active element and passive element, so that the current stress of each element is reduced and system response improved. In order to maximize output capacity of the system, DC-Links of each module were connected together to compose a parallel system.

3. Proposed Power Control Method

3.1 Sequence of proposed power control method

The mathematical equation for proposed PI power controller is given by Eq. (1).

\[
P_{\text{Load}} = i_{dc,\text{Load}} \times v_{dc,\text{Load}}
\]

\[
P_{\text{slave}} = \frac{P_{\text{Load}}}{N}
\]

\[
P_{\text{slave}} = i_{dc,\text{BB2}} \times v_{dc,\text{BB2}}
\]

\[
P_{\text{avg}} = P_{\text{slave}} - P_{\text{load}}
\]

\[
v_{dc,\text{BB2}}(t) = K_p P_{\text{avg}}(t) + K_i \int P_{\text{avg}}(t) dt
\]

\(P_{\text{Load}}\) is the whole power supplied to the load, \(P_{\text{slave}}\) is power supplied in slave module. And through the variable \(N\), the slave module can be operated with desired power.

Fig. 3 shows the sequence of the proposed power control method. When Converter 1 assumes the master module and Converter 2 assumes the slave module, the whole system controls voltage in a no-load condition. When controlling voltage that is normally required by each system, Parallel MC is operated to connect the system in parallel.

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**Fig. 2.** DC distribution system for building applications.

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Each converter voltage control (no-load condition)\

Parallel MC ON, parallel connection\

\[ V_{d,MC} \times I_{d,MC} > 0 \rightarrow P_{slow} = 0 \]

Load MC ON, load connection\

Load power measurement, \( P_{Load} = i_{d,Load} \times v_{d,Load} \)

\[ P_{slow} = 0 \rightarrow P_{slow} = \frac{(i_{d,Load} \times v_{d,Load})}{N} \]

**Fig. 3.** Proposed control method sequence.

Circulating current can be caused to the system by parameter inconsistency such as difference in filter, line impedance constituent, gain error of sensor, and characteristics of the power semiconductor switching element. To minimize circulating current, the master module maintains voltage control, the slave module performs power control and controls the power consumption at 0[W]. When power of slave module is controlled at 0[W], Load MC is operated to connect the load. Power consumption of each system can be obtained through the entire power consumed for the load divided by the variable \( N \). This is used as power reference for the slave module.

### 3.2 Control block diagram

**Fig. 4.** Control block diagram of DC distribution system for simulation and experiment.

**Table 1.** System parameters for experimental set up for DC distributions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power</td>
<td>( P )</td>
<td>120[kVA]</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>( V )</td>
<td>380[V \text{rms}]</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>( f_s )</td>
<td>5[kHz]</td>
</tr>
<tr>
<td>VSC filter line inductance</td>
<td>( L_{\text{f}} )</td>
<td>120[mH]</td>
</tr>
<tr>
<td>VSC filter Capacitance</td>
<td>( C_f )</td>
<td>50[\mu F]</td>
</tr>
<tr>
<td>VSC boost inductance</td>
<td>( L_p )</td>
<td>500[\mu H]</td>
</tr>
<tr>
<td>VSC DC-Link capacitance</td>
<td>( C_{\text{vdc}} )</td>
<td>10200[\mu F]</td>
</tr>
<tr>
<td>VSC DC-Link Voltage</td>
<td>( V_{d,\text{vdc}} )</td>
<td>700[V \text{rms}]</td>
</tr>
<tr>
<td>Buck-boost inductance</td>
<td>( L_{\text{bp}} )</td>
<td>700[\mu H]</td>
</tr>
<tr>
<td>Buck-boost DC-link capacitance</td>
<td>( C_{\text{bc}} )</td>
<td>20400[\mu F]</td>
</tr>
<tr>
<td>Over-current protection inductance</td>
<td>( L_p )</td>
<td>500[\mu H]</td>
</tr>
<tr>
<td>Buck-boost DC output voltage</td>
<td>( V_{d,\text{out}} )</td>
<td>380[V \text{rms}]</td>
</tr>
</tbody>
</table>

**4. Simulation**

Table 1 shows system parameters for the simulation and experiment. The input voltage is three-phase 380[V \text{rms}] and 60[Hz]. The VSC DC-Link voltage controlled by three-phase AC/DC converter is 700[V \text{rms}] and Buck-Boost DC-Link voltage controlled by bi-directional DC/DC converters is 380[V \text{rms}]. The system switching frequency is 5[kHz]. To generate circulating current in the simulation, the slave module was forced to be sensed 5[V] less voltage.
than the master module.

Fig. 5 shows the waveform of circulating current during the parallel operation of DC distribution system. When the system is in parallel connection, the voltage difference of capacitors composed in parallel in the output side of each module temporarily causes in-rush current. Thereafter, circulating current flows the entire system. The current generated in the master module flows in the positive direction and that in the slave module flows in the negative direction. Therefore, it shows that circulating current is generated in the system. If it is not inhibited, the circulating current increases in size, therefore, protection circuit can be operated. It must be improved because the risk appears even after load connection.

Fig. 6 shows the voltage of system according to entire operation sequence when the proposed power control method was applied. When DC-Link is discharged in the beginning of operation, the diode is rectified through the initial charging circuit to charge voltage that is as $\sqrt{3}$ times high as that of the grid voltage to DC-Link for prevent inrush current to the capacitor. Thereafter, PWM is started to boost to 700[Vdc]. When the voltage control is completed in AC/DC converter, DC/DC converter also performs voltage control to supply consistent voltage of 380[Vdc] to DC BUS. It was shown that the voltage control is performed normally even in drastic change in load.

Figs. 7 and Fig. 8 show the waveform of simulation in which the proposed control method was applied and current and power is normally distributed to each system. Over-current caused by collision of the voltage generators in each module is further prevented by adding a protection inductor. According to the power control method, circulating current is controlled at 0[A] in the slave module. Also it shows that the current and power is distributed to each module even after load is connected by power controller.

5. Experimental Result

The experimental setup is shown in Fig. 9 and the same system will be composed in parallel. The experiment setup consists of the control and power part including AC/DC converter and DC/DC converter, control part including the DSP controller, initial charging and discharging circuit part, parallel connection part, and filter part.

To verify the validity of the proposed control method, a experiment was conducted under the same conditions and the same method as in the simulation at 28[kW] load.

Fig. 10 shows the circulating current generated in the parallel system, when the proposed control method is not applied. In parallel connection, a temporary in-rush current is generated due to collision of voltage source of the output side in the system. Thereafter, the inconsistency of
parameters in each module causes circulating current. Size of the currents are positive in the master module and negative in the slave module, so flow of circulating current is from the master module to the slave module. It is shown that the inrush current in the experimental is generated in a small amount because it is connected in parallel with almost equal output voltage, unlike in the simulation.

Fig. 11 shows controlling circulating current generated in the system to nearly 0[A] by applying the control method that includes PI power controller. In addition, inrush current is eliminated due to protection inductor.

Fig. 12 shows the waveform of the experiment that shows voltage and current in the DC distribution system is controlled normally. The operation sequence of the whole
Fig. 10. The waveform of inrush current and circulating current without proposed PI power controller.

Fig. 11. The waveform of output current in parallel connection using proposed PI power controller.

Fig. 12. The waveform of DC-Link voltage and output current using proposed PI power controller.

Fig. 13. The waveform of output current in load connection using proposed PI power controller.

Fig. 14. The waveform of DC-BUS voltage and output current in heavy load connection and removal.

Fig. 15. The waveform of output current is controlled by power reference.

system was the same as in the simulation. By controlling the circulating current in the system to 0[A], the whole system is operated stably.

Fig. 13 shows that, when 28[kW] of load is connected and 14[kW] of power reference is given to the slave module, equal current is distributed to each module.

Fig. 14 shows the waveform of the enlarged DC-BUS voltage and output current when 28[kW] of load is connected and removed. Proposed system of this paper supplies the voltage for DC distribution BUS. Therefore, the voltage fluctuation is an important factor. If the range of voltage fluctuation is large when heavy load is connected and removed, it will cause damage to the devices linked to the BUS. However, the DC- BUS voltage of this system instantaneously increases and decreases less than 10[V][380[V] is based on less than 2.63%], when 28[kW] of load is connected and removed in a moment.

Fig. 15 shows that power sharing to each module controlled by power reference. Initially, as the power reference of the slave module is set at 0[kW], the master module takes 28[kW] of load alone. When the power reference of the slave module is 14[kW], each module takes equal power that is half of the entire load power.

Fig. 16 shows the waveform of load-sharing when the slave module operated after the master module operated alone. Initially, the master module start operation and control voltage at 380[V]. After that the master module takes 28[kW] of load alone. And then the slave module
Fig. 16. The waveform of DC-Link voltage and output current when the slave module operated after the master module operated.

Fig. 17. The waveform of power sharing of each module by power reference

Fig. 18. The waveform of circulating current in no-load connection

starts operation and connects to the load. The slave module has reference of corresponding to one-half of the total power. Therefore, the two modules share power of corresponding to one-half of the total power.

Fig. 17 shows the waveform of power sharing of each module by power reference. Initially, the master module takes alone all of total power. And then the slave module starts operation and connects to the load. At this time, the slave module has reference of corresponding to 1/4 of total power. And then the slave module has reference of corresponding to 2/4, 3/4 and 4/4 of total power. Thus this system can be operated with desired power through the power reference.

Fig. 18 shows that power sharing to each module controlled by power reference under no load condition. Initially, the circulation current controlled to 0[A] by power reference. Then 10[kW] power reference of the slave module is given. When the two modules are connected parallel to each other, the other module can be recognized as a load. Therefore the current circulates throughout the system by power reference of the slave module. As a result, it shows that current corresponding to 10[kW] circulates from the slave module to the master module.

6. Conclusion

In this paper, a power control method to reduce circulating current caused during parallel operation is proposed. Also, in-rush current caused by collision of voltage generators in parallel connection was prevented by additionally installing a protection inductor. By using a power control method including PI power controller, the simulation and experiment results verified that the current and power is distributed to each module as system want according to power reference. Therefore, it can be utilized for a large capacity parallel system such as DC distribution system. Also, it can improve reliability of the entire parallel operation system and secure for the possibility of expansion in the future.

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